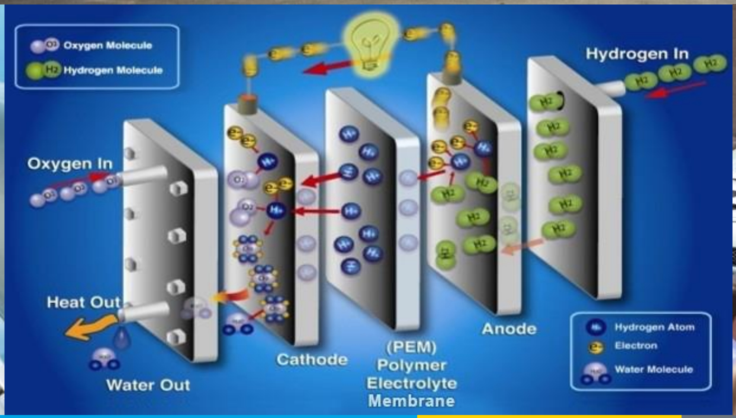
Technology Developments to Enable On-Board Hydrogen Storage

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Advanced Clean Cars Symposium: The Road Ahead

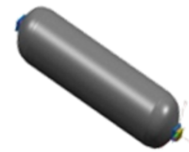
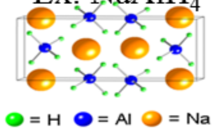
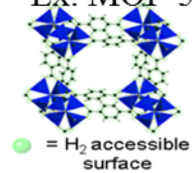
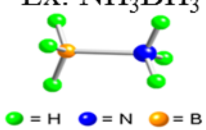
Diamond Bar, California

September 27, 2016

Ned T. Stetson, Ph.D.

Hydrogen Storage Program Manager
Fuel Cell Technologies Office
U.S. Department of Energy

Hydrogen Storage Technology Development: Parallel paths to address near and long-term needs

Dual approach	Technology Focus		Barriers and R&D Focus
Hydrogen Storage → Near-Term Approach	700 bar Compressed		•Lower Cost Carbon Fiber •Improved Composites •Conformable designs •Lower Cost BOP
Hydrogen Storage → Longer-Term Approach	Cold / Cryo-Compressed		•System Engineering •Advanced Insulation •Improved Dormancy •Composite Development
	Metal Hydrides	Ex. $NaAlH_4$ 	•Higher Material Capacity •System Cost •Fill Time •Onboard Efficiency
	Sorbents	Ex. MOF-5 	•Higher Material Capacity •System Cost •Dormancy •WTP Efficiency
	Chemical H_2 Storage	Ex. NH_3BH_3 	•Lower Cost Off-board Regen •System Cost •Gravimetric Density

Near-term – address cost and performance of 700 bar H_2 storage;
Long-term – develop advanced technologies with potential to meet all targets

Current status for H_2 Storage on Fuel Cell Vehicles

HYUNDAI

TOYOTA

HONDA

H_2 fuel cell electric vehicles

- **Models available for lease or sale** in certain geographic areas around the world
- **700 bar (70 MPa; 10,000 psi) onboard storage**
- Type IV composite overwrapped pressure vessels
- **Driving range: 265-312 miles***
- **700 bar refueling infrastructure** being deployed in certain geographic areas
- **Fill times as low as 3 minutes**

* Ranges based on EPA estimates for 2016 model year vehicles: https://www.fueleconomy.gov/feg/fcv_sbs.shtml

H_2 fuel cell forklifts/pallet jacks

- **350 bar onboard storage**
- Type I/III/IV pressure vessels
- Performance benefits over battery forklifts
- 350 bar refueling infrastructure deployed, but at a premium over battery charging

Initial commercialization occurring with compressed H_2 storage

Examples of On-Road Demonstrations

FCEV	Storage Technology	Chassis Style	Fuel Economy in miles / kg H_2 (City / Hwy)	Driving Range (miles)	Year Reported
Ford Focus	350 bar	Compact Car	48/53	200	2006
Nissan X-trail	350 bar	Compact SUV	no ref	229	2006
Chevrolet Equinox	700 bar	Compact SUV	47	199	2007
Kia Borrego	700 bar	Full-size SUV	60	470	2010
Toyota Highlander FCHV-adv	700 bar	Full-size SUV	58	350	2011
Honda Clarity	350 bar	Mid-size Car	60/60	240	2012
Mercedes-Benz F-Cell	700 bar	Subcompact Car	52/53	190	2012
Hyundai Tucson	700 bar	Compact SUV	50	265	2014
Toyota Mirai	700 bar	Subcompact Car	66	312	2015


Photo Credit: Ford Motor
Ford Focus

Chevrolet Equinox

Photo Credit: GM


Photo Credit: Hyundai Motor
Hyundai Tucson

Toyota Mirai

Photo Credit: Toyota Motor


Photo Credit: Honda Motor
Honda Clarity

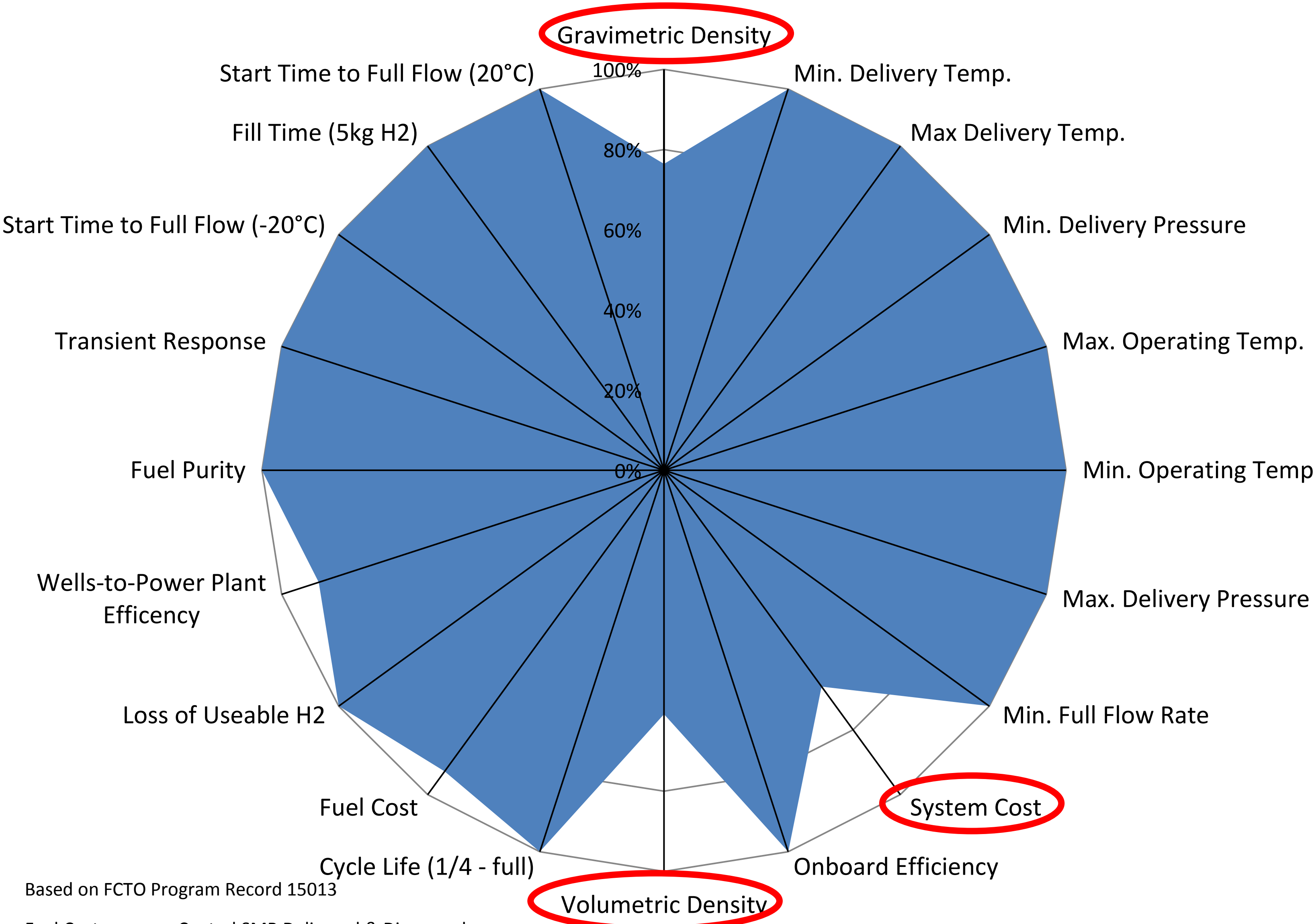
Mercedes-Benz F-Cell

Photo Credit: Daimler AG

Compressed gas storage delivers acceptable driving ranges for <u>some</u> vehicle platforms

700 Bar H_2 Storage System Performance

Projected Against DOE 2020 Targets



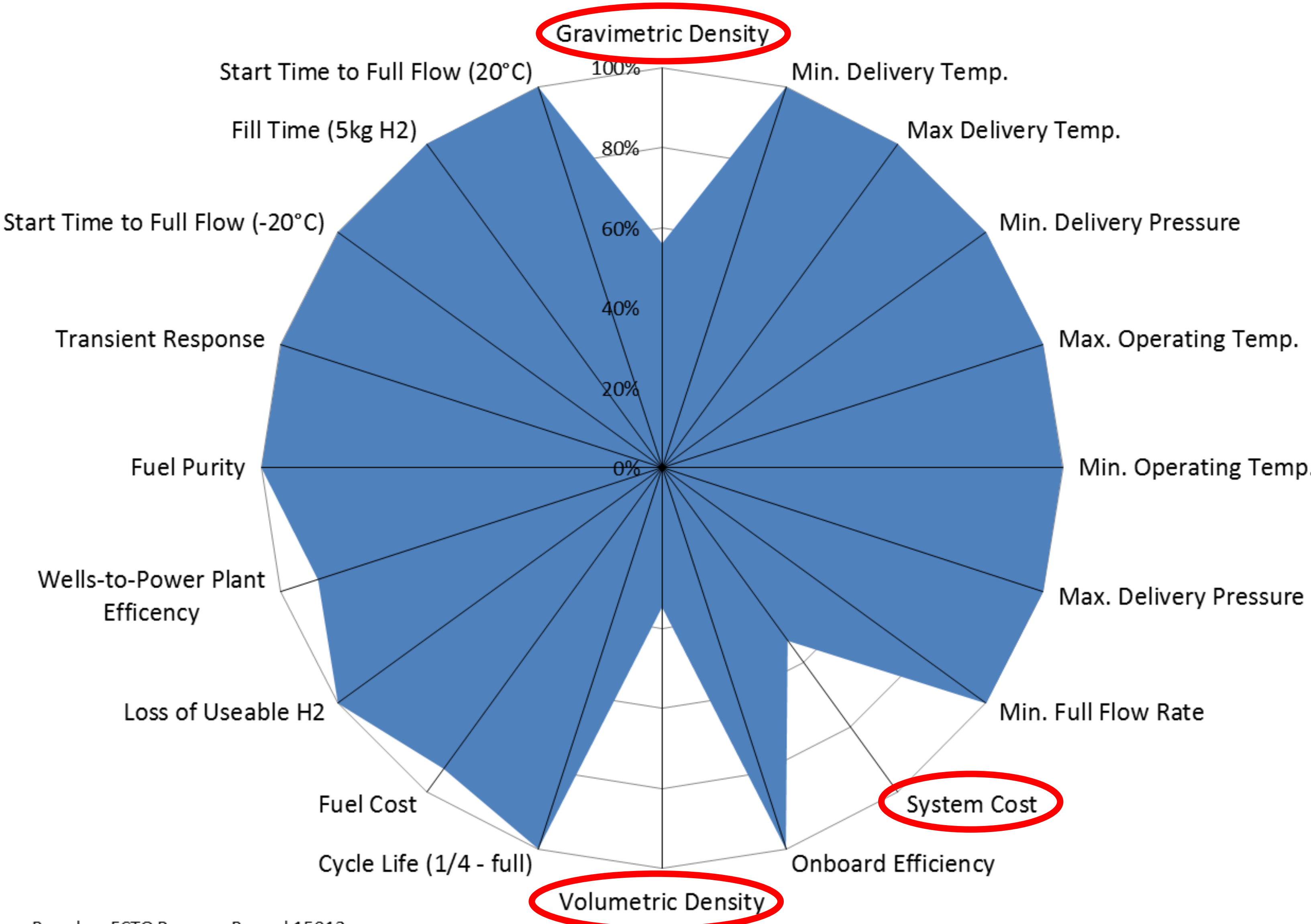
Based on FCTO Program Record 15013

Fuel Cost assumes Central SMR Delivered & Dispensed

Source U.S. Department of Energy

Current Technology- 700 Bar H_2 Storage System Performance

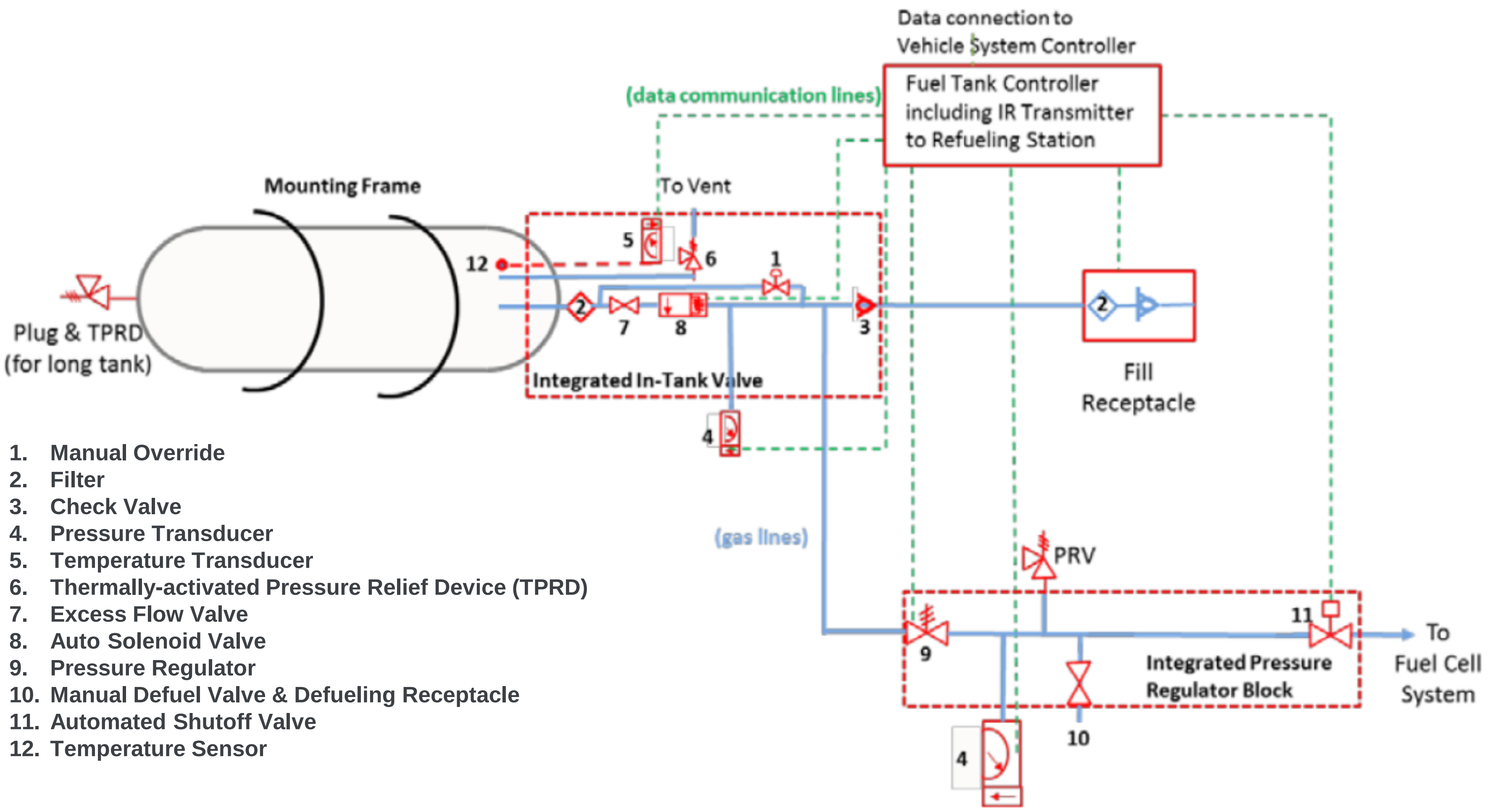
Projected Against DOE Ultimate Full Fleet Targets



Based on FCTO Program Record 15013
Source U.S. Department of Energy

Baseline 700 Bar System Configuration

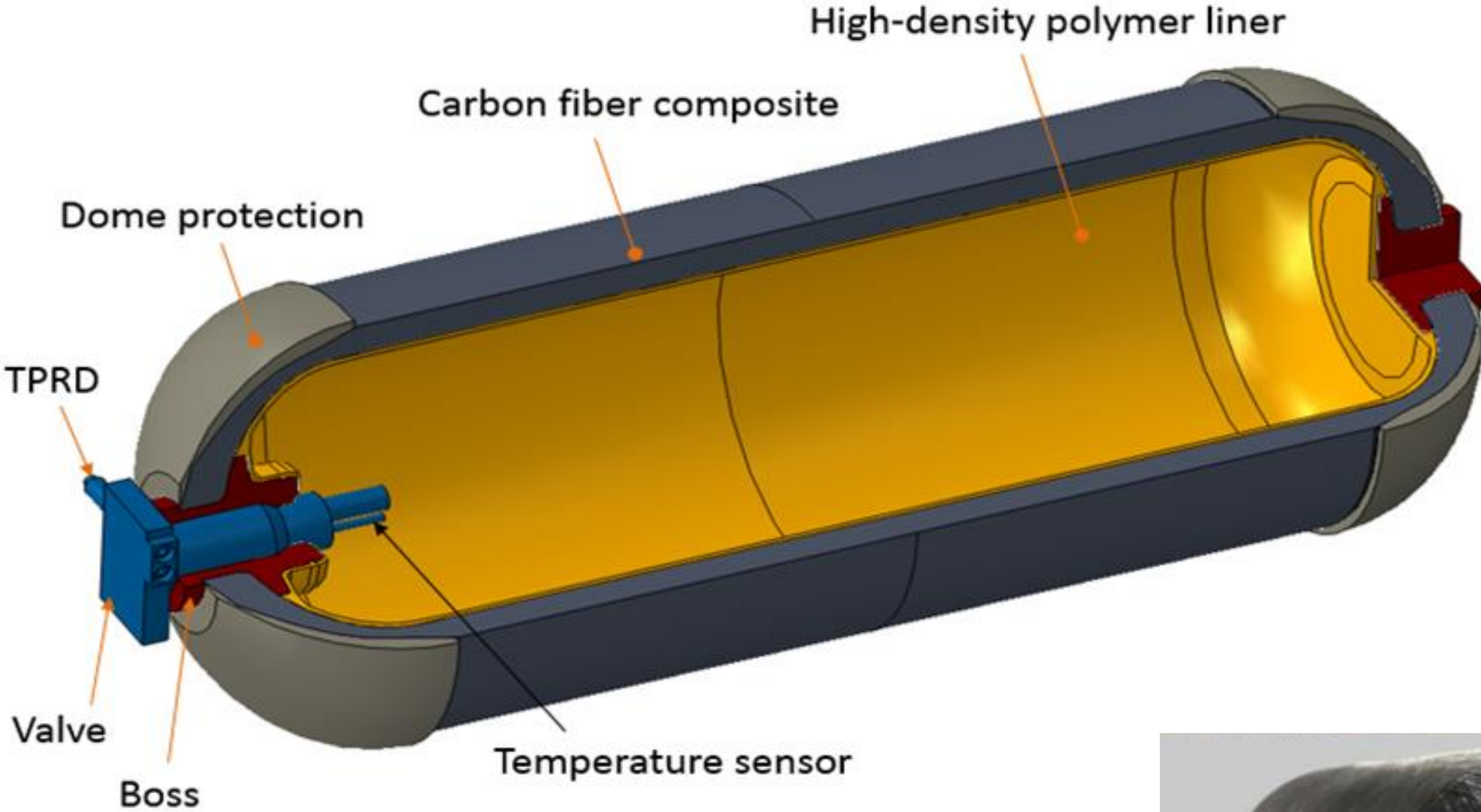
Single-tank configuration is used in cost and performance models



1. Manual Override
2. Filter
3. Check Valve
4. Pressure Transducer
5. Temperature Transducer
6. Thermally-activated Pressure Relief Device (TPRD)
7. Excess Flow Valve
8. Auto Solenoid Valve
9. Pressure Regulator
10. Manual Defuel Valve & Defueling Receptacle
11. Automated Shutoff Valve
12. Temperature Sensor

G. Ordaz, C. Houchins, and T. Hua, “Onboard Type IV Compressed Hydrogen Storage System – Cost and Performance Status 2015,” DOE Hydrogen and Fuel Cells Program Record #15013, Nov. 25, 2015.

Composite Overwrapped Pressure Vessels

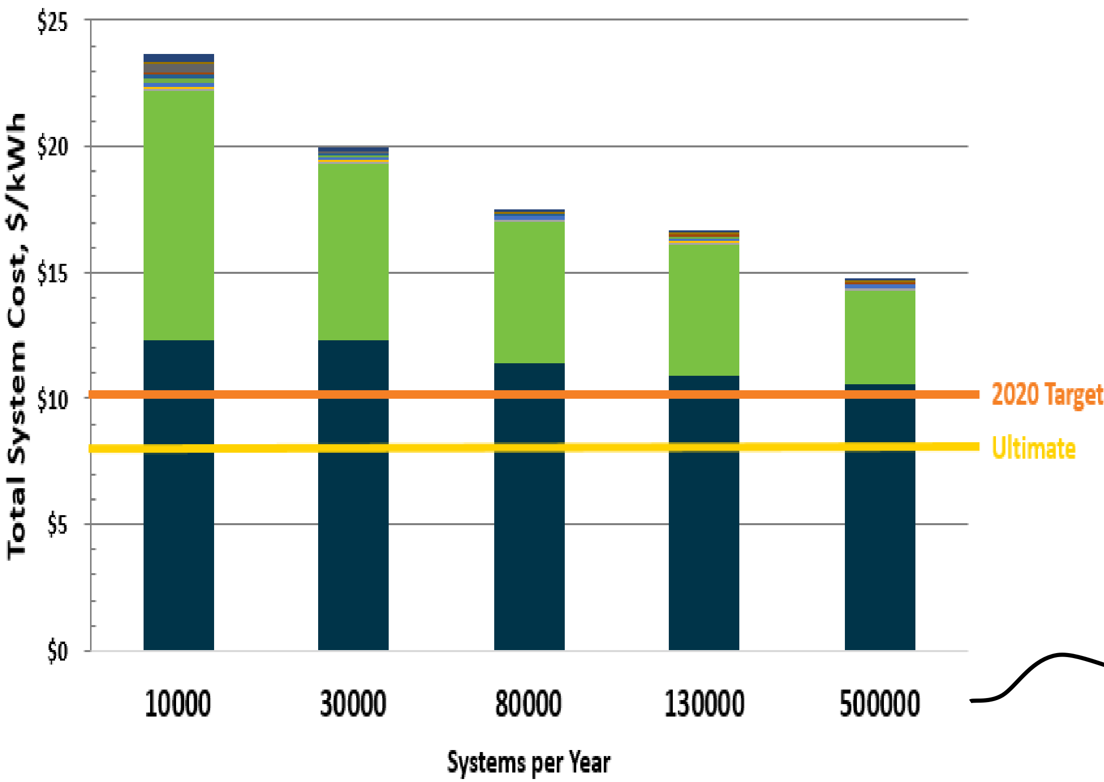


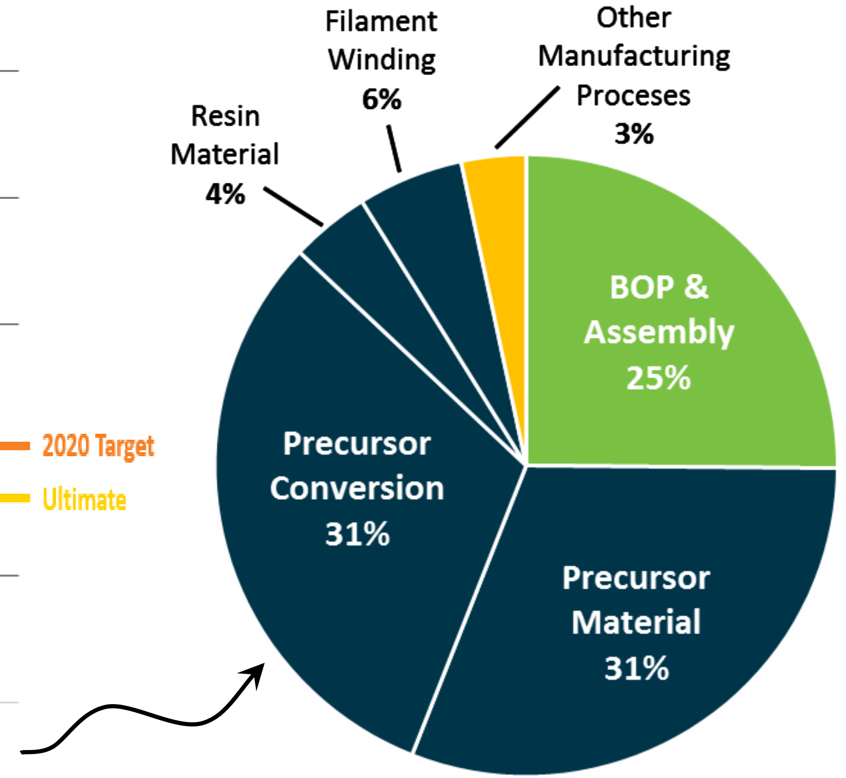
TPRD = Thermally Activated Pressure Relief Device

Credit: Process Modeling Group, Nuclear Engineering Division. Argonne National Laboratory (ANL)

Credit: Stako, 2015

700 Bar System Cost





https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf

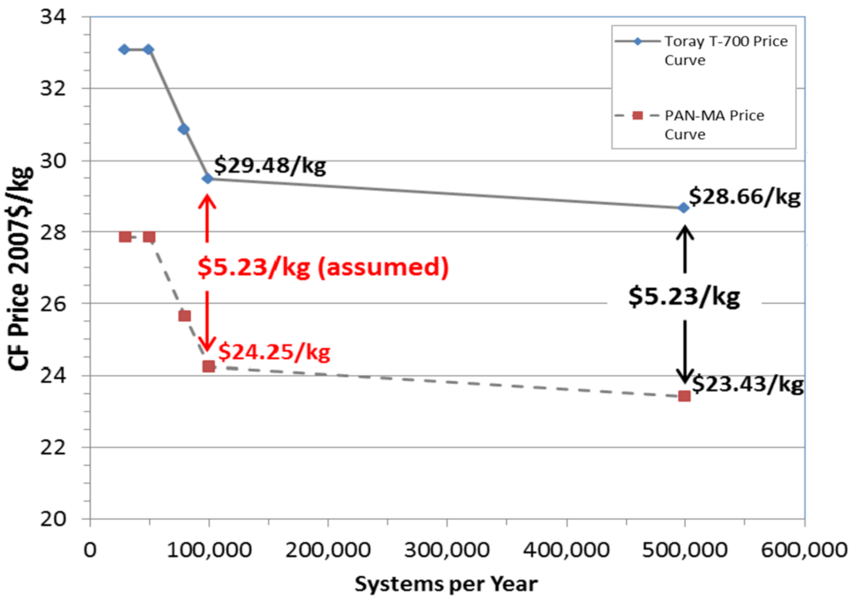
Source U.S. Department of Energy

Cost targets cannot be met without significant reduction in high-strength carbon fiber composite costs – Where can the costs be reduced?

Lower Cost Precursors for Carbon Fiber

Commercial Textile (PAN/MA) Precursors
(Oak Ridge NL) – Project completed

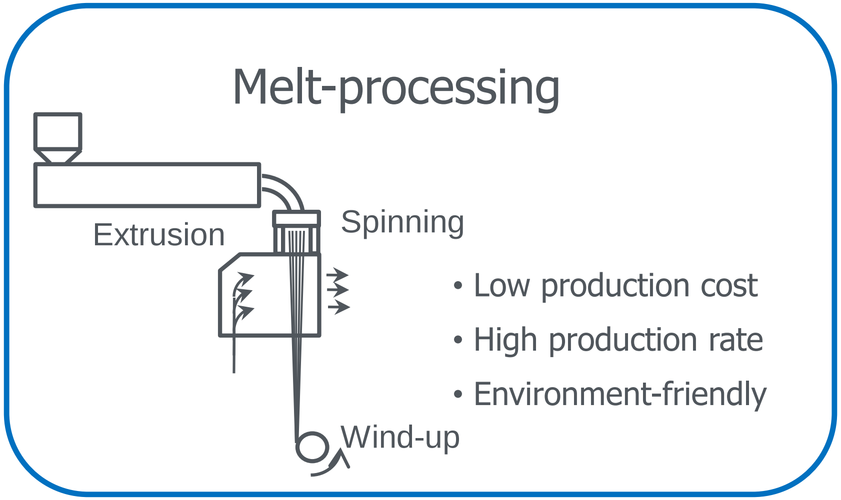
- **Precursors account for ≥55% of cost of carbon fibers**
- **Textile PAN fibers ~25% lower cost than conventional PAN fiber precursors**
- **Potential fast-track, drop-in replacement precursor**
- **Projected CF costs of $23.43/kg, savings of ~$5/kg compared to Toray T-700S**



G. Ordaz, C. Houchins, and T. Hua, "Onboard Type IV Compressed Hydrogen Storage System – Cost and Performance Status 2015," DOE Hydrogen and Fuel Cells Program Record #15013, Nov. 25, 2015.

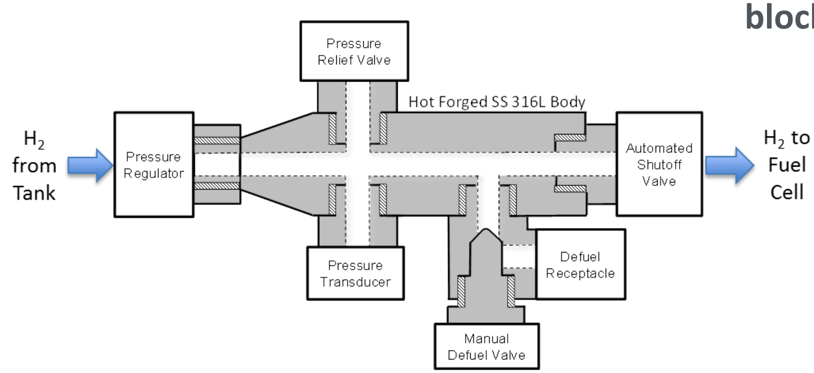
Melt Processable PAN Precursors
(Oak Ridge NL)

- **Target: >25% reduction in costs of manufacturing of carbon fiber**
- **Cost reduction achieved through lower capital costs and lower processing costs vs conventional wet spinning processes**
- **Alternative melt processable formulations to be developed and demonstrated**
- **Feasibility demonstrated, scale-up in process**



Balance of Plant Cost Reductions

Component Integration



Integrated pressure regulator block

Analysis Year	BOP Assumptions/Changes	BOP Cost (2007$/kWh)
2013 (DOE Record)	Majority of vendor quotations, limited by product availability	$4.98/kWh
2014	DFMA® analysis of integrated in-tank valve and pressure regulator quotation update	$4.37/kWh
2015 (DOE Record)	Integrated pressure regulator block will reduce number of fittings (translates to other H_2 storage systems)	**$3.64/kWh**

G. Ordaz, C. Houchins, and T. Hua, "Onboard Type IV Compressed Hydrogen Storage System – Cost and Performance Status 2015," DOE Hydrogen and Fuel Cells Program Record #15013, Nov. 25, 2015.

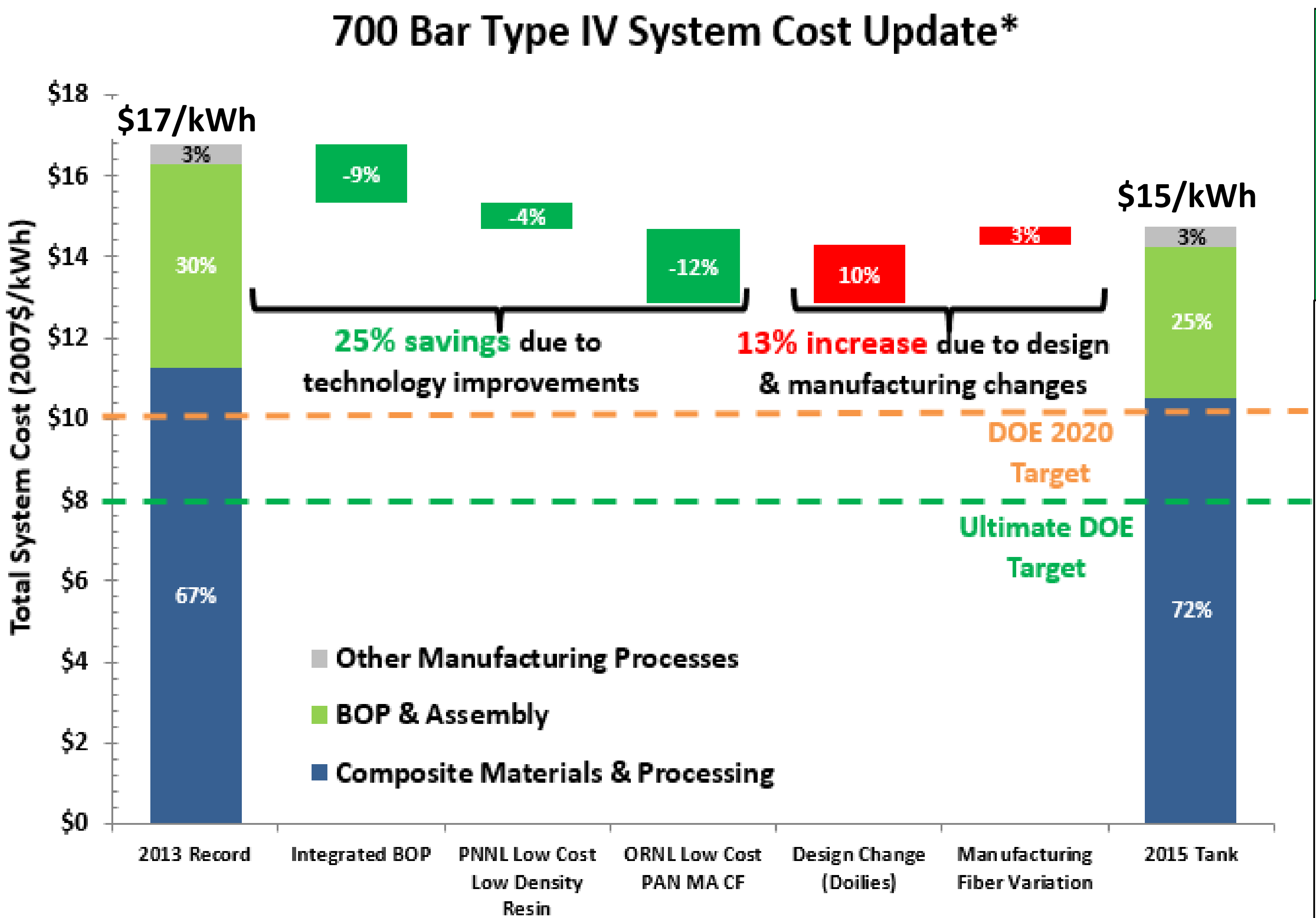
Alternative Materials

Combined empirical and computational approach to identify alternative materials for use in hydrogen service (SNL)

- Fatigue properties versus reduction in tensile strength
- Computationally determine stacking fault energy and strategies to control it

Material	Raw Material Cost	Yield Strength (MPa)	Weight Savings (%)	Relative Material Cost (%)
316L (A)	*1.0*	*170*	*0*	*100*
316L (CW)	1.2	570	**70**	**36**
21Cr-6Ni-9Mn (XM-11)	0.8	540	**69**	**33**
304L (CW)	1.0	540	**68**	**26**
Nitronic 60	1.0	415	**59**	**48**
SCF 260	1.1	965	**82**	**23**

Updated system cost - 700 bar single tank config.



*At 500k units/yr. Based on Program Record 15013
Source U.S. Department of Energy

Strategies to Reduce Cost of Current Technology

- Low-cost carbon fiber precursors
- Balance of plant (BOP) integration
- Low-cost and low-density resins

12% Net Cost Reduction since 2013

Current FCEVs use dual tank configurations

Honda Clarity

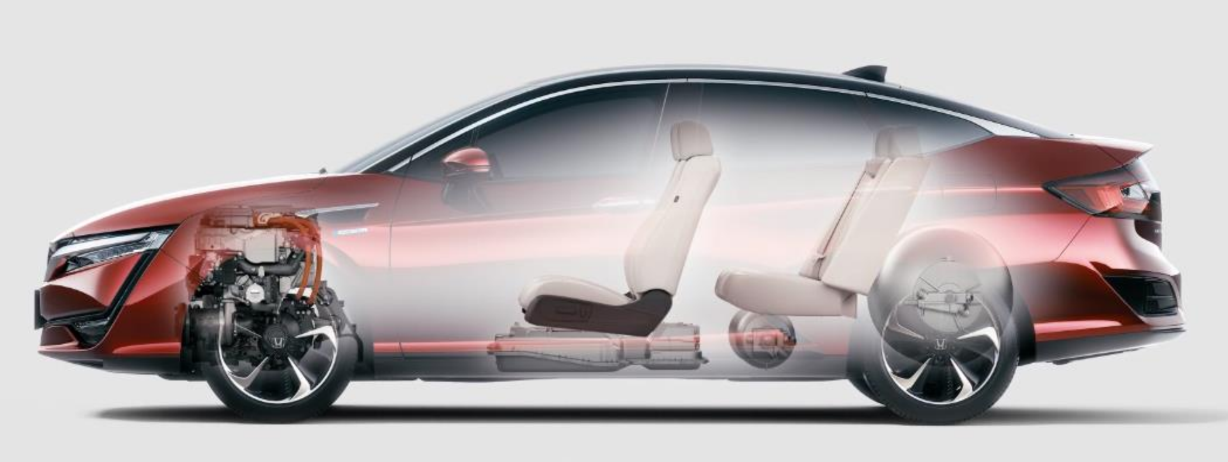


Photo Credit: Honda Motor

Hyundai Tucson Fuel Cell

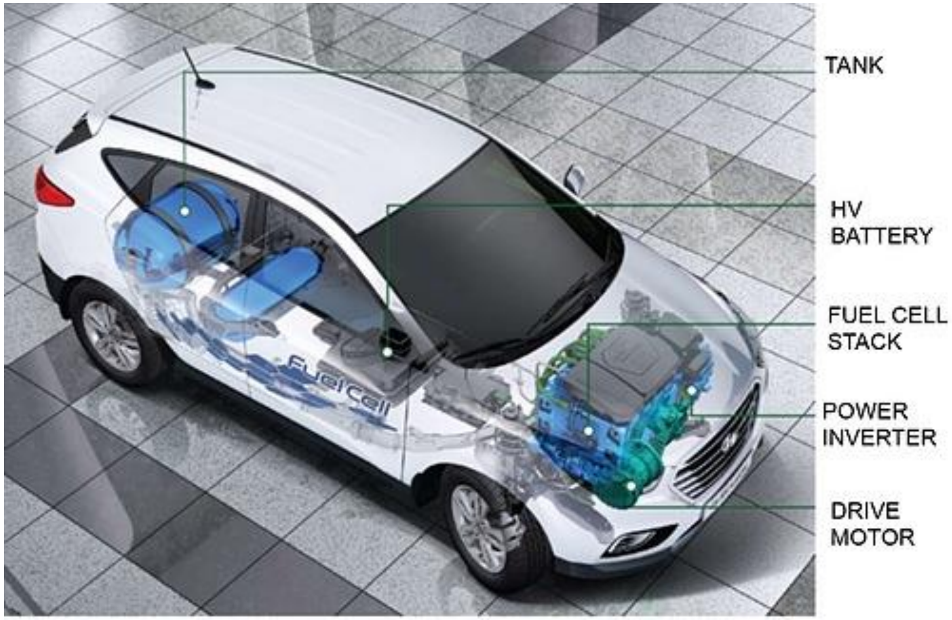


Photo Credit: Hyundai Motor

Toyota Mirai

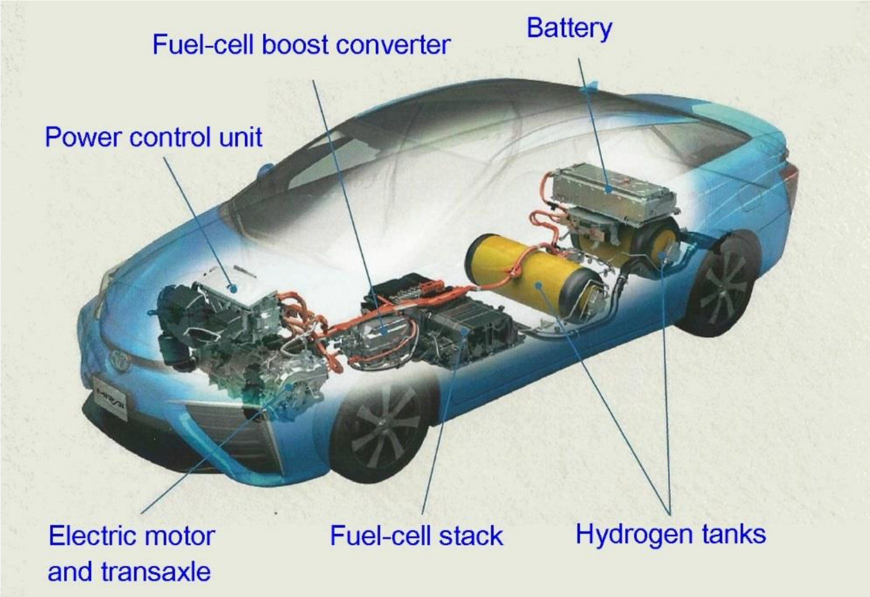
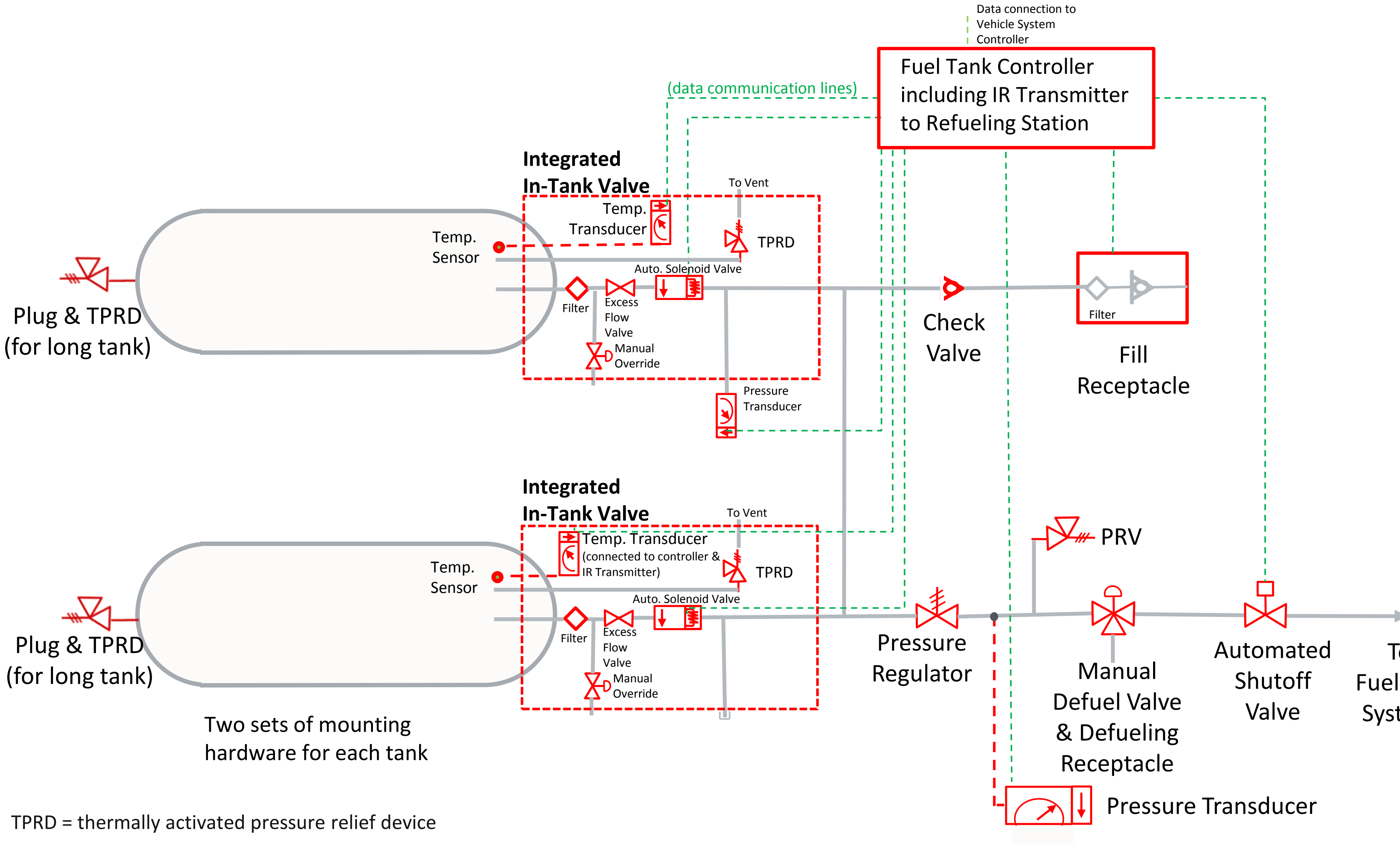


Photo Credit: Toyota Motor

700 Bar System Configuration

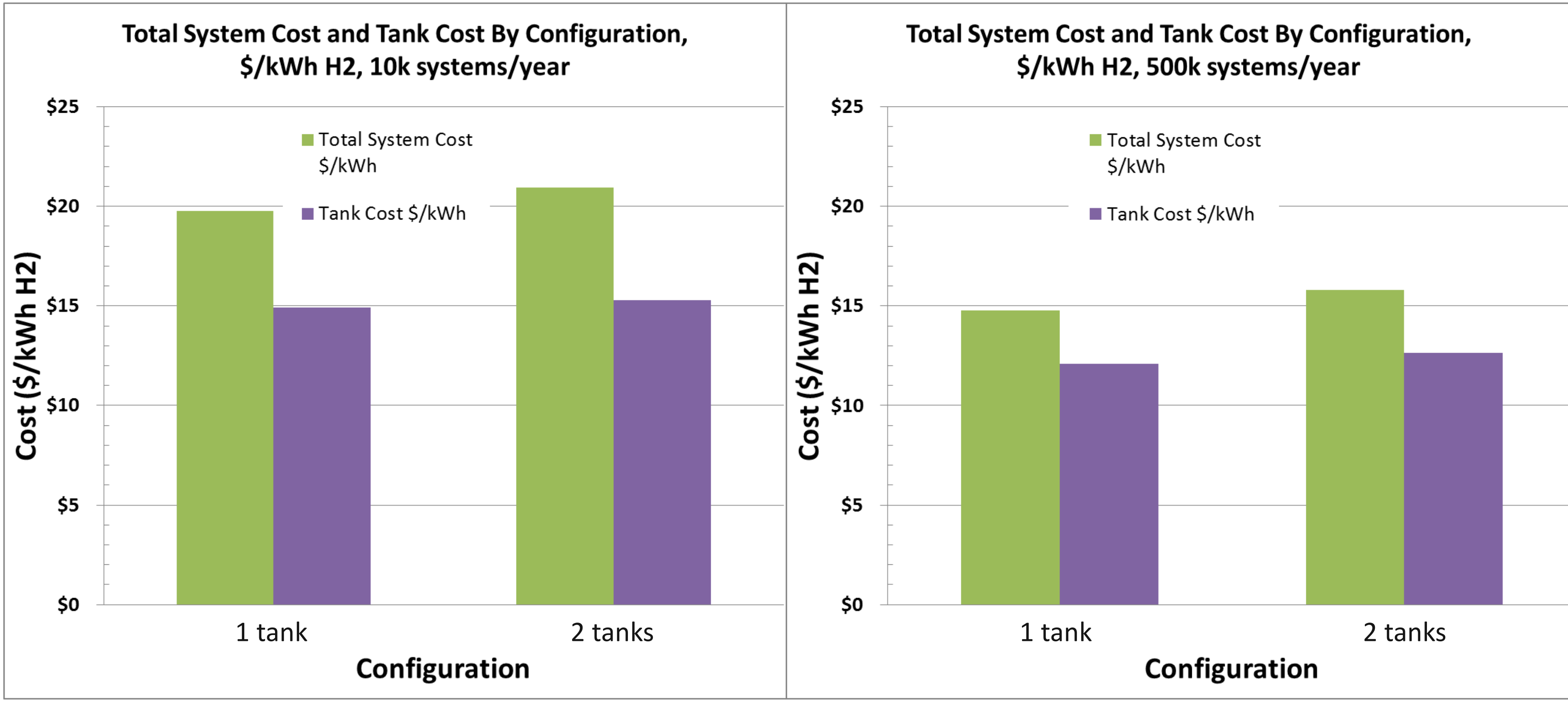
Dual-tank configurations are currently used onboard all commercial FCEVs today
Significant increase in cost due to redundancies in balance of plant components



TPRD = thermally activated pressure relief device

Brian James, Strategic Analysis; Hydrogen and Fuel Cell Technologies Annual Merit Review and Peer Evaluation, 2013.
https://www.hydrogen.energy.gov/pdfs/review13/st100_james_2013_o.pdf

Impact of # of tanks on system cost



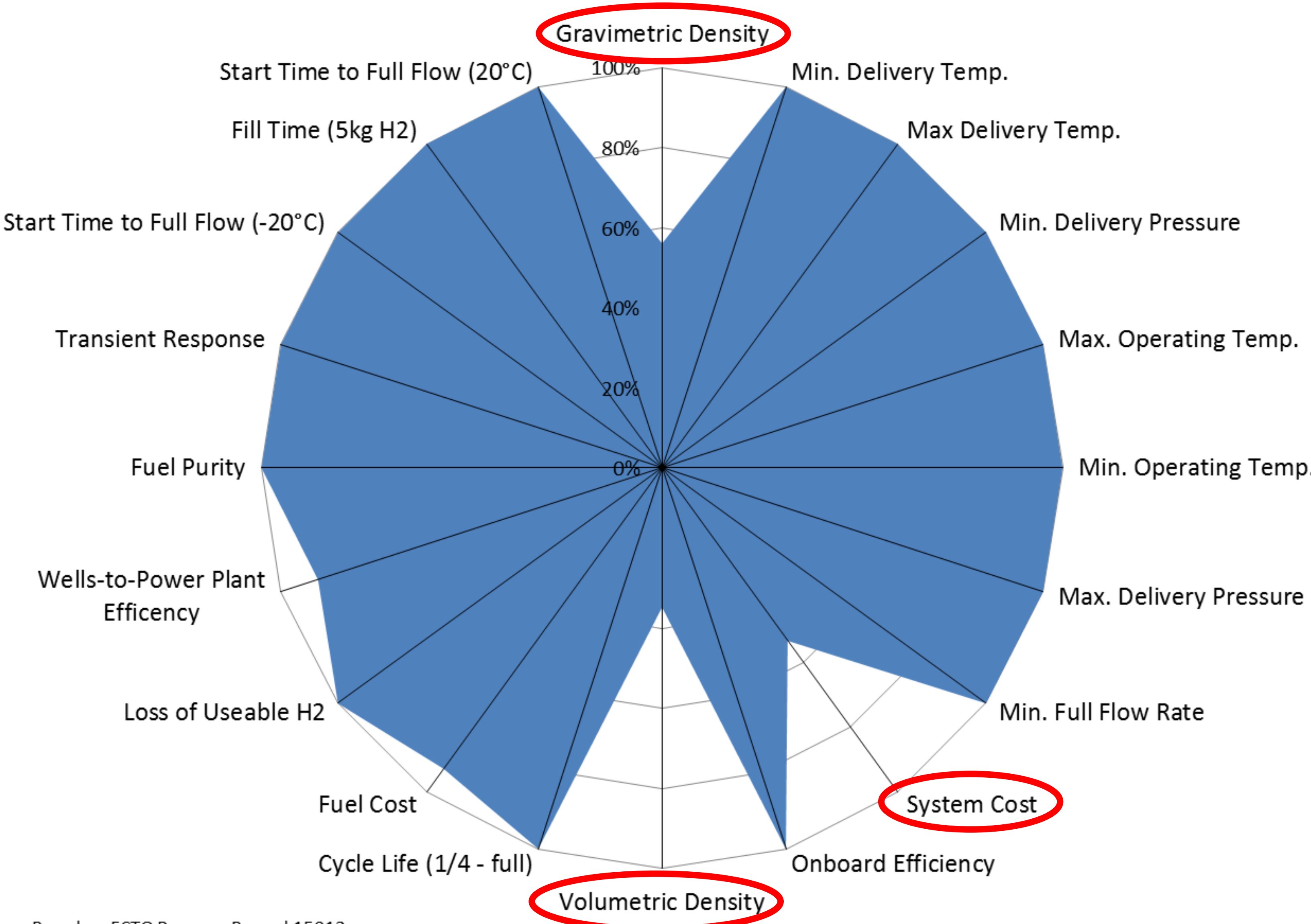
Based on 5.6 kg usable H_2 capacity systems (5.6 or 2.8 kg per tank), Type IV COPVs, L/D ratio of 3.0, 700 bar operation, safety factor 2.25

B. James, A. Spisak, Strategic Analysis, presented to the US. DRIVE H_2 Storage Technical Team, Nov. 15, 2012

Balance of plant accounts for bulk of cost increase in multi-tank configurations

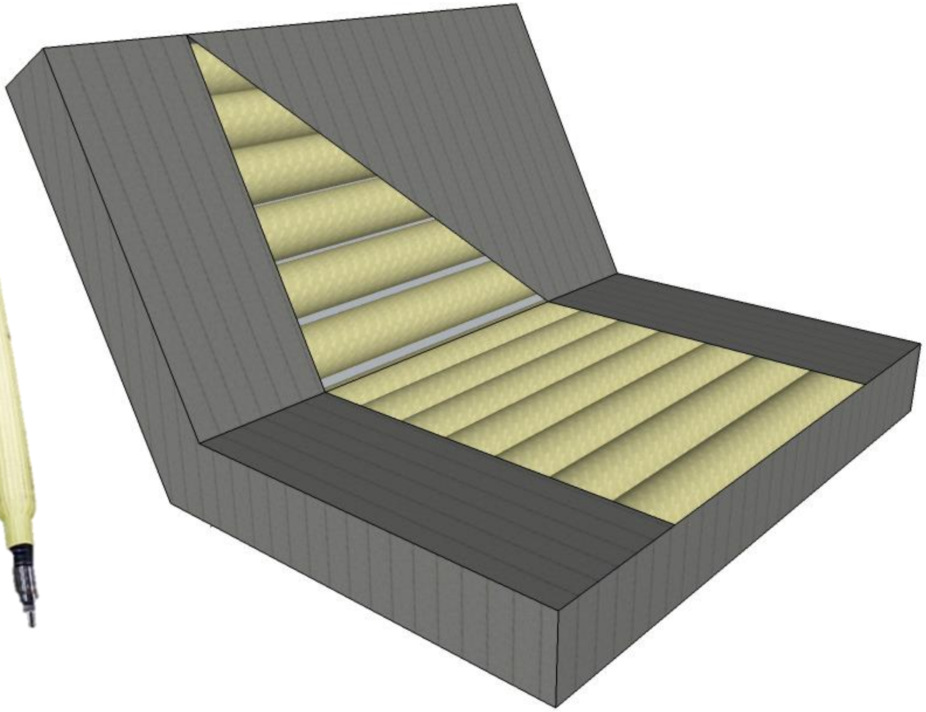
Current Technology- 700 Bar H_2 Storage System Performance

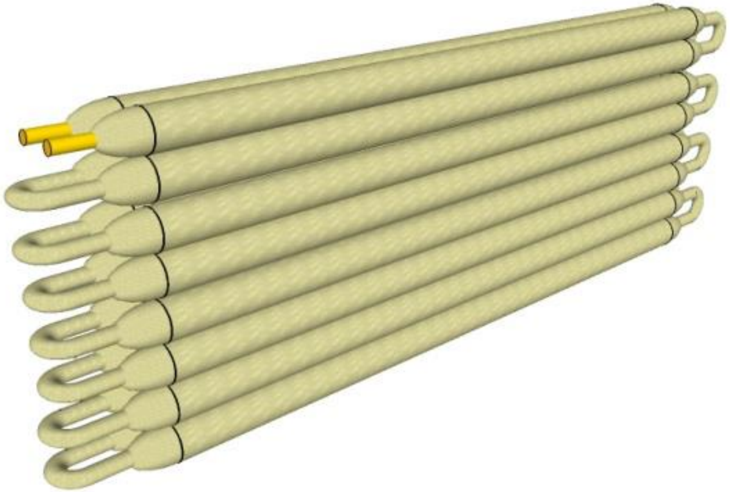
Projected Against DOE Ultimate Full Fleet Targets



Based on FCTO Program Record 15013
Source U.S. Department of Energy

Conformable tanks

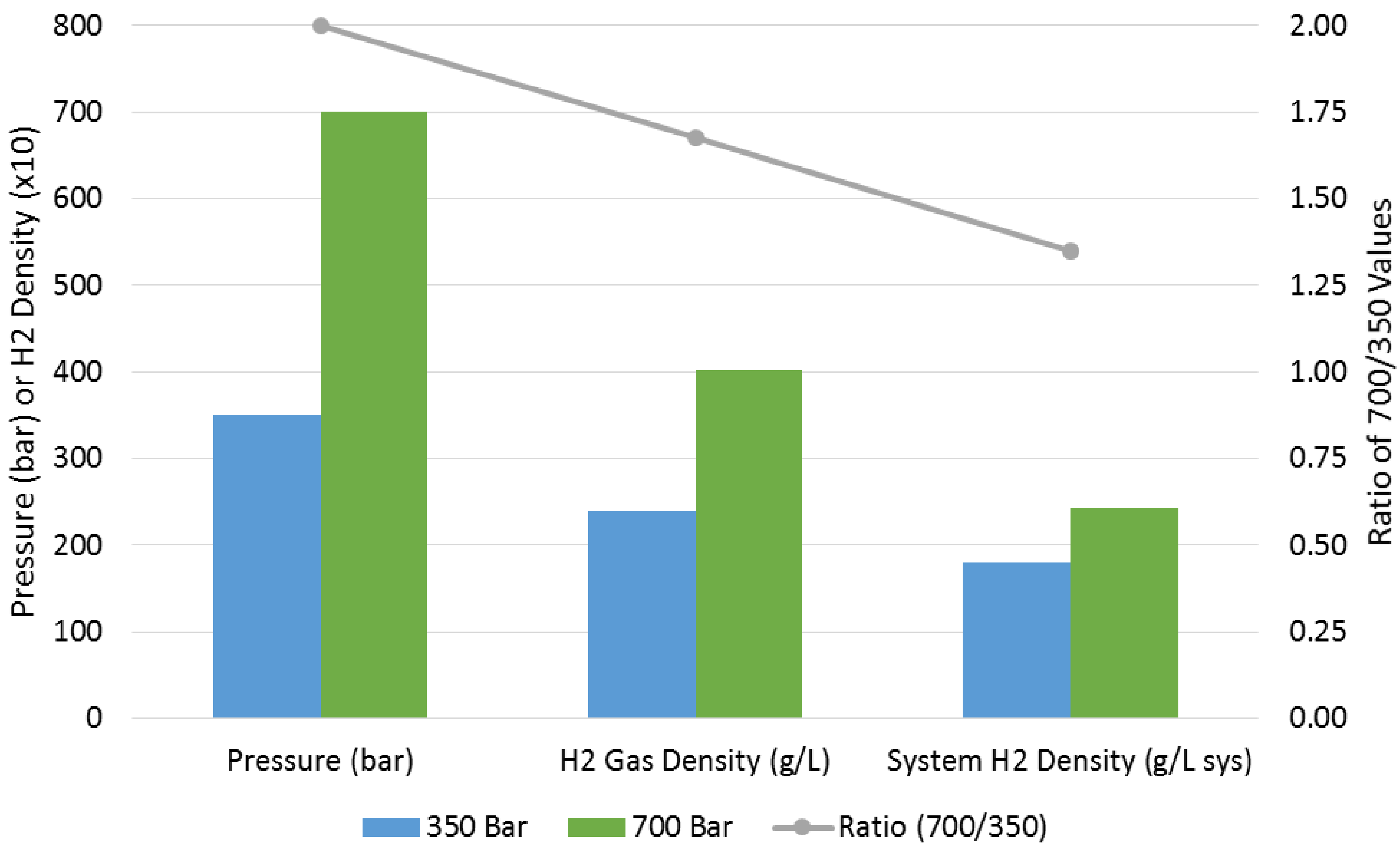




Concept being developed by Center for Transportation and the Environment

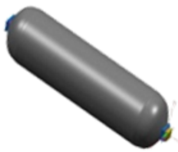
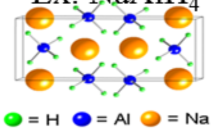
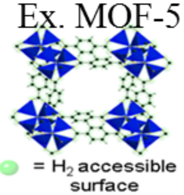
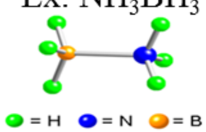
Conformable pressure vessels offer potential of improved packaging onboard vehicles, eliminating need for multiple cylinders and redundant BOP

Comparison of H_2 Densities at 350 and 700 Bar



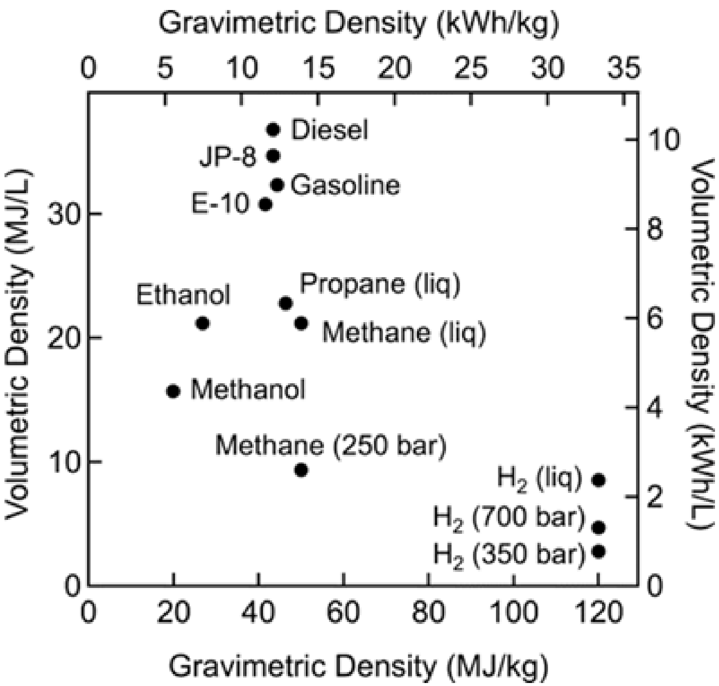
Going to higher pressure is not a solution to improving H_2 density

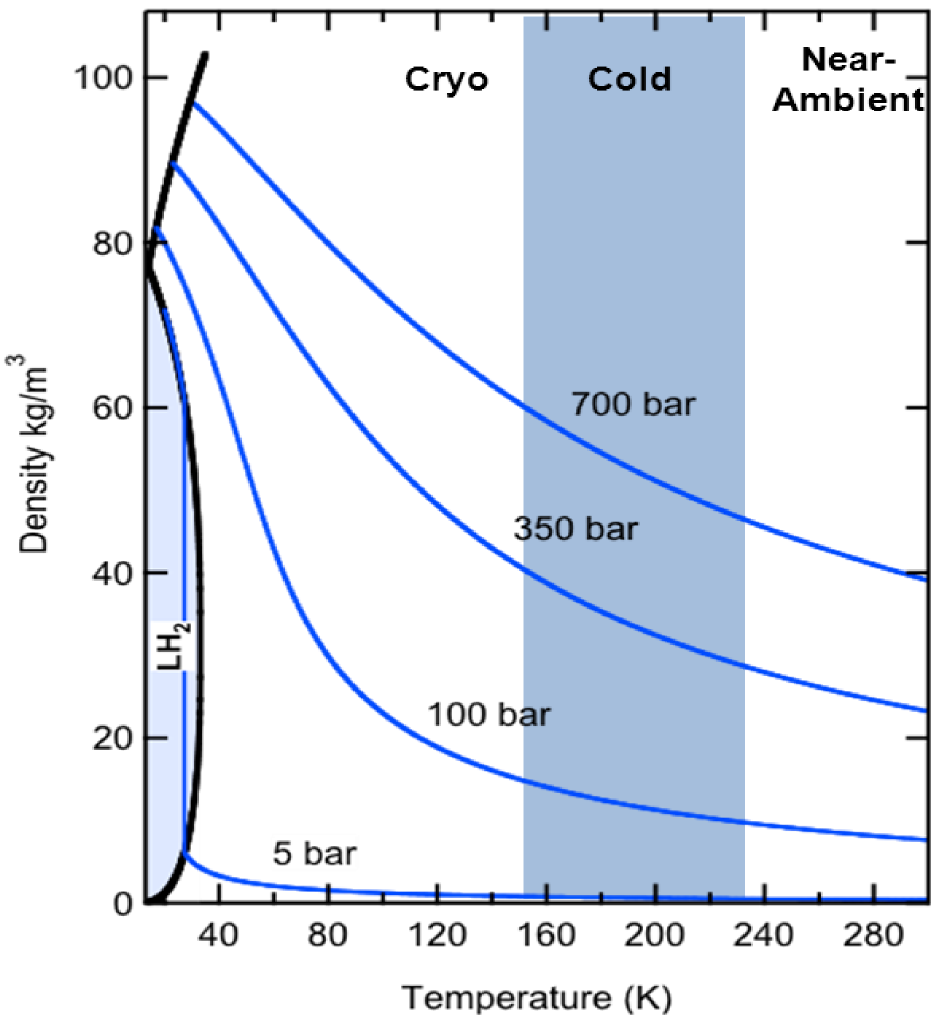
Hydrogen Storage Technology Development: Parallel paths to address near and long-term needs

Dual approach		Technology Focus		Barriers and R&D Focus
Hydrogen Storage	Near-Term Approach	700 bar Compressed		•Lower Cost Carbon Fiber •Improved Composites •Conformable designs •Lower Cost BOP
	Longer-Term Approach	Cold / Cryo-Compressed		•System Engineering •Advanced Insulation •Improved Dormancy •Composite Development
		Metal Hydrides	Ex. $NaAlH_4$ 	•Higher Material Capacity •System Cost •Fill Time •Onboard Efficiency
		Sorbents	Ex. MOF-5 	•Higher Material Capacity •System Cost •Dormancy •WTP Efficiency
		Chemical H_2 Storage	Ex. NH_3BH_3 	•Lower Cost Off-board Regen •System Cost •Gravimetric Density

Near-term – address cost and performance of 70 MPa H_2 storage;
Long-term – develop advanced technologies with potential to meet all targets

Higher H_2 densities are achievable through use of lower temperatures





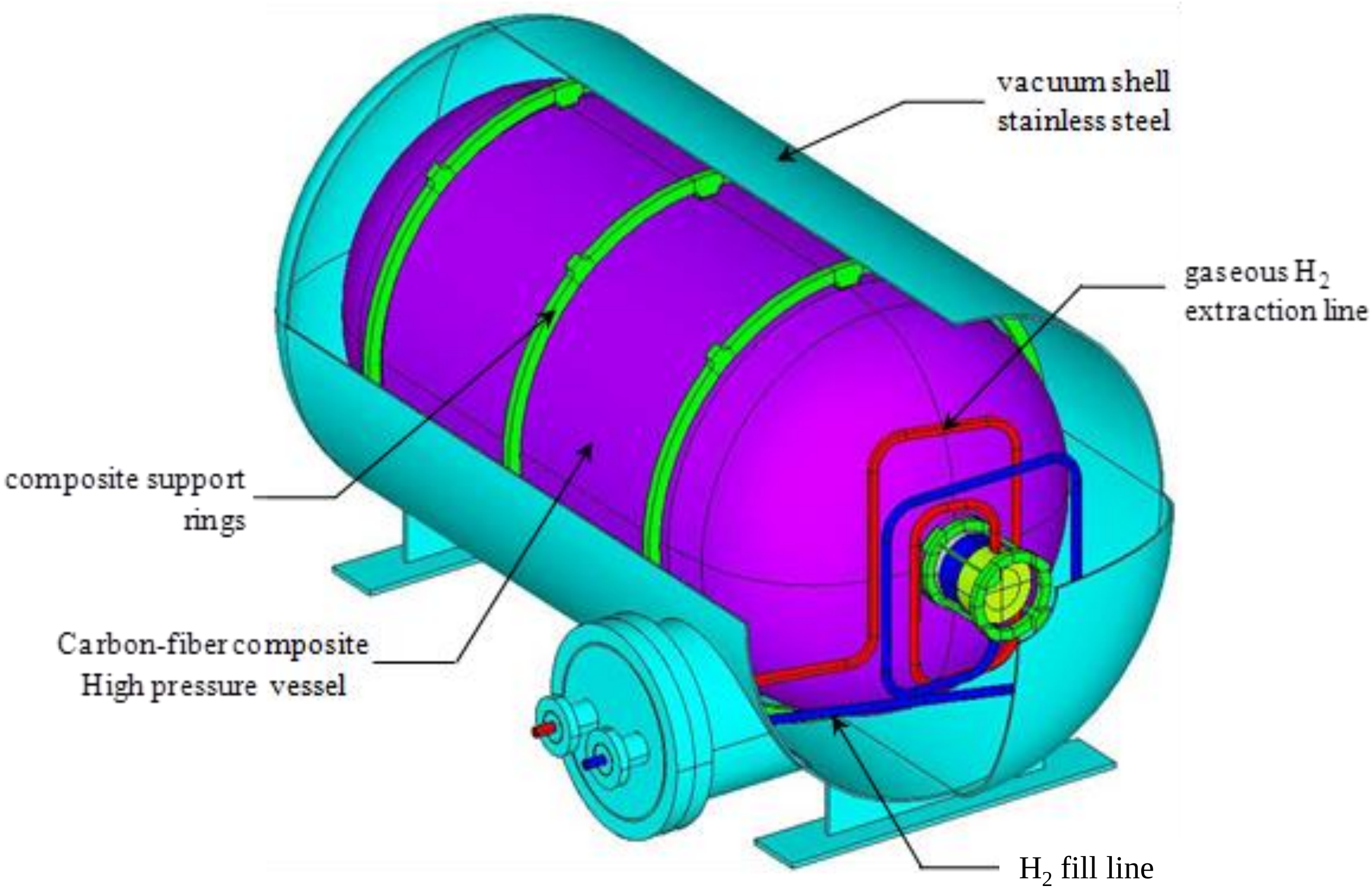
Lower Temperatures

lead to…

Higher Energy Densities

Source U.S. Department of Energy

Sub-ambient compressed H_2 storage



Source: Lawrence Livermore National Laboratory

High-performance insulation used to extend dormancy and reduce pressure build up and venting of H_2 due to heat leakage

Examples of sub-ambient storage efforts

Organization	Pressure	Temperature	H_2 Sys. Density	Application
BMW [1]	300 bar	~40 – 80 K	≥ 30 g/L	LDVs
LLNL [2]	700 bar	~40 – 80 K	50 g/L	LDVs
PNNL [3]	500 bar	~200 K	25 g/L	LDVs
ANL [4]	tbd	~40 – 80 K	tbd	Buses
HSECoE [5]	≤ 100 bar	80 -160 K	21 g/L	LDVs, sorbents

1: based on K. Kunze, O. Kircher, BMW Group, presented at the Cryogenic Cluster Day, Oxford, September 28, 2012. https://www.stfc.ac.uk/stfc/cache/file/F45B669C-73BF-495B-B843DCDF50E8B5A5.pdf

2: based on S. Aceves, G. Petitpas, V. Switzer, LLNL, presented at the Hydrogen and Fuel Cell Technologies Annual Merit Review and Peer Evaluation Meeting, June 17, 2014. https://www.hydrogen.energy.gov/pdfs/review14/st111_aceves_2014_o.pdf

3: based on D. Gotthold, PNNL, presented at the Hydrogen and Fuel Cell Technologies Annual Merit Review and Peer Evaluation Meeting, June 9, 2016. https://www.hydrogen.energy.gov/pdfs/review16/st101_gotthold_2016_o.pdf

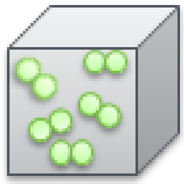
4: based on personal communications about R&D being carried out by R. Ahluwalia, ANL, 2016.

5: based on D. Anton, SRNL/HSECoE, presented at the Hydrogen and Fuel Cell Technologies Annual Merit Review and Peer Evaluation Meeting, June 9, 2016. https://www.hydrogen.energy.gov/pdfs/review16/st004_anton_2016_o.pdf

A range of pressures and temperatures are being investigated and have not yet been optimized

Long Term Strategy-H_2 Materials Based Storage: Potential for Higher H_2 Densities

Physical Storage



700 bar

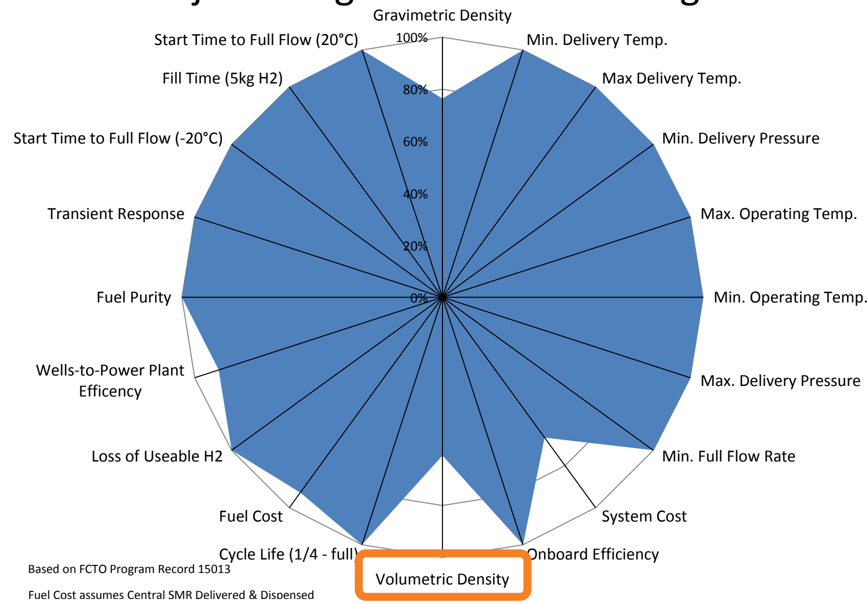
Gen 2 vehicles

40g/L

Theoretical limitations prevent 700 bar from meeting all onboard targets

700 Bar H2 Storage System Performance

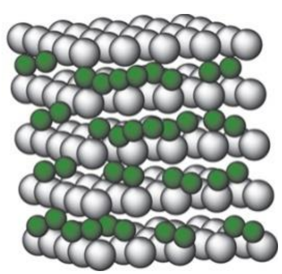
Projected Against DOE 2020 Targets



Based on FCTO Program Record 15013

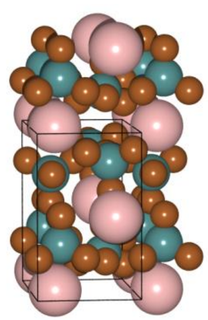
Fuel Cost assumes Central SMR Delivered & Dispensed

Materials Storage



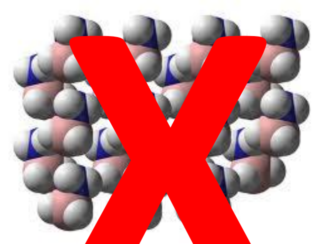
interstitial hydrides

~100-150 g H_2/L



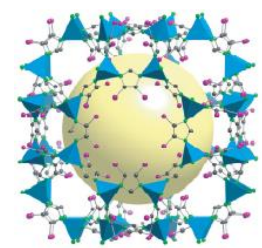
complex hydrides

~70-150 g H_2/L



chemical storage

~70-150 g H_2/L



sorbents

≤ 70 g H_2/L

Reference

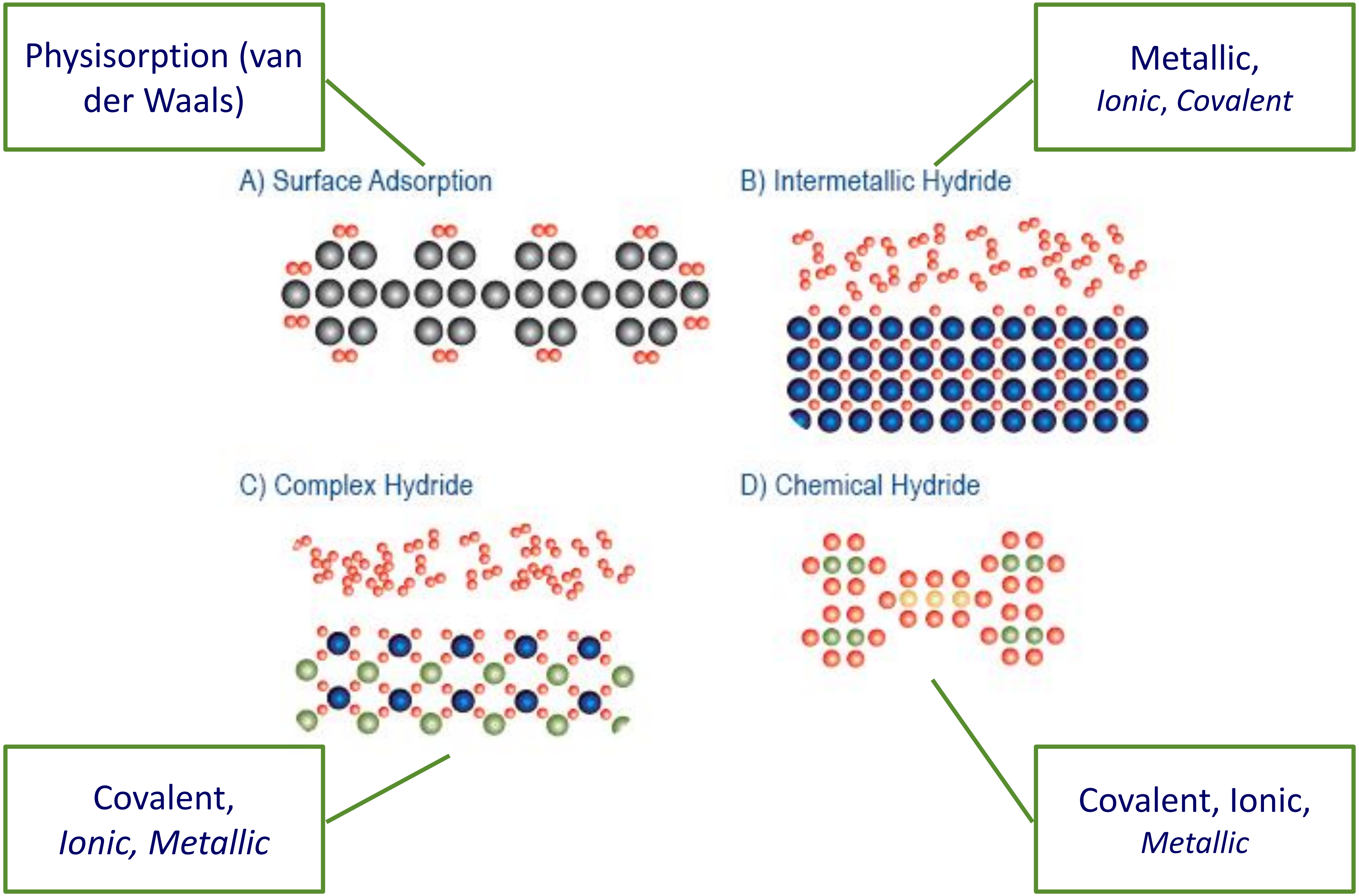
water

111 g H_2/L

Higher densities = potential to meet system targets

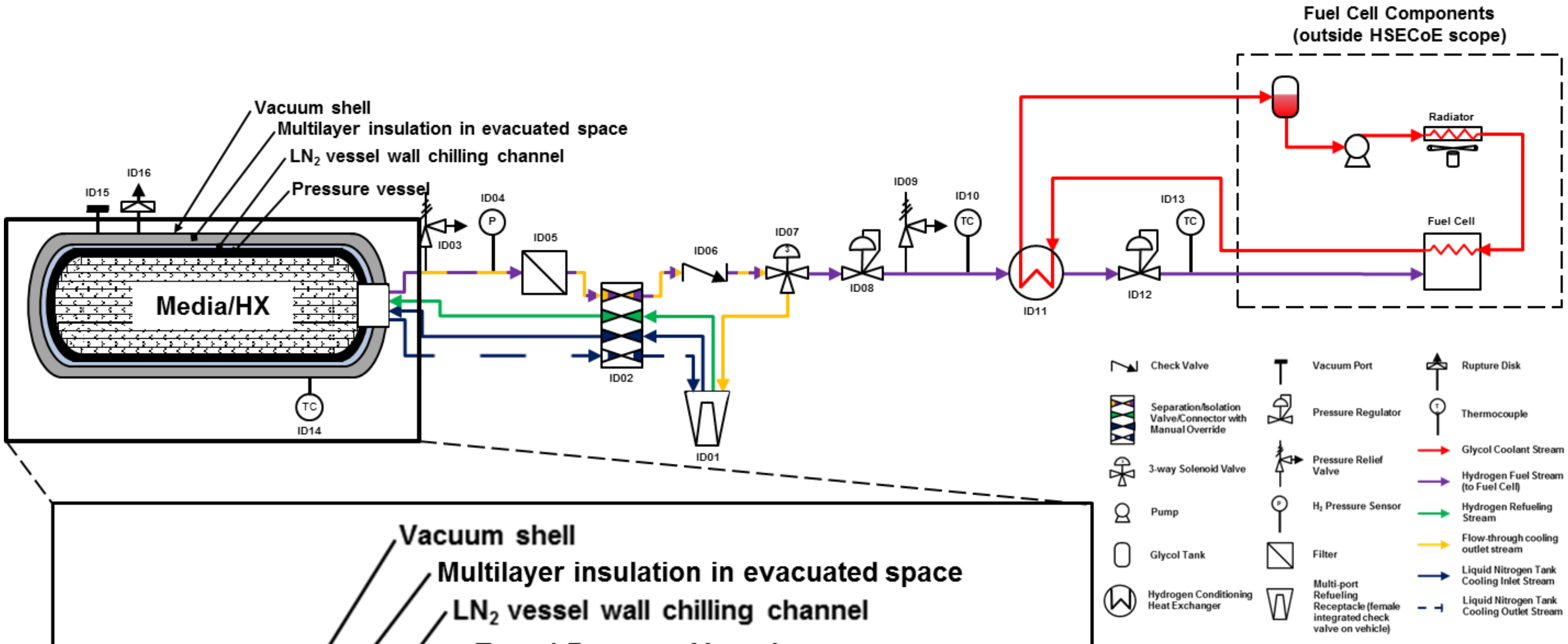
Source U.S. Department of Energy

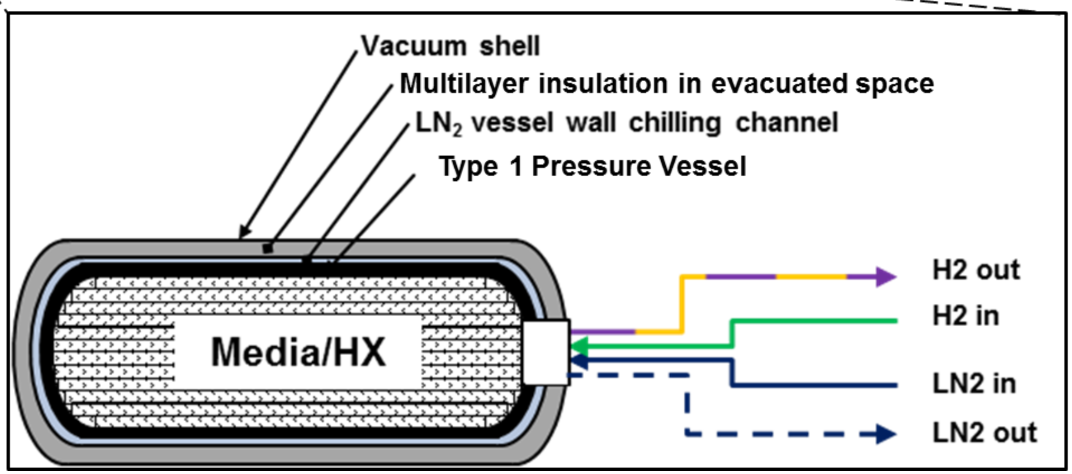
Bonding type in materials

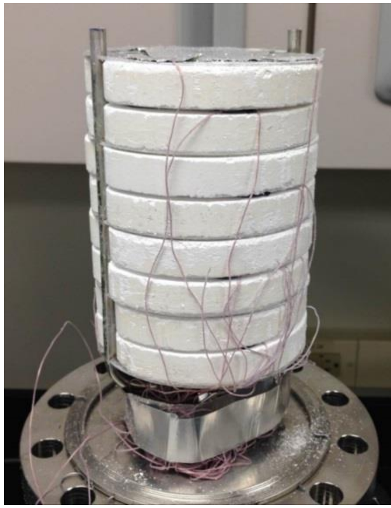


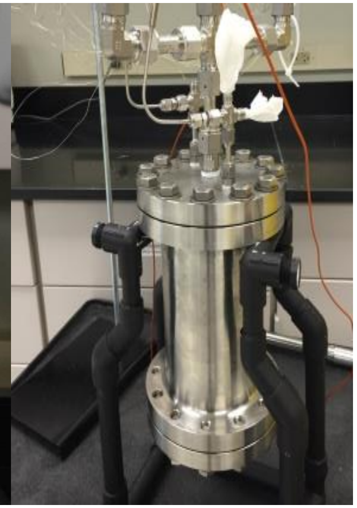
Source U.S. Department of Energy

Example of a sorbent prototype system









Material-based systems must be able to exchange heat due to the endo/exothermic nature of the hydrogen sorption processes

D. Anton, SRNL, Hydrogen and Fuel Cell Technologies Annual Merit Review and Peer Evaluation Meeting, June 9, 2016.
https://www.hydrogen.energy.gov/pdfs/review16/st004_anton_2016_o.pdf

Strategies for increasing energy density

Method	H_2 Density	Advantage	Disadvantage
compression	40 g/L (700 bar)	simple, mature	low energy density, cost
liquefaction	70 g/L (20 K)	high density, low-pressure	energy penalty, cryogenic, dormancy
cold/cryo-compressed	up to ~90 g/L (700 bar, 40 K)	high density, Simple, fast refueling	cryogenic, high-pressure, dormancy, energy penalty
Materials-based			
metal hydrides	up to 150 g/L	high density, low-pressure	weight, cost, complexity
sorbents	up to 70 g/L (?)	high density, low-pressure, kinetics	cryogenic, complexity, dormancy
liquid carriers	up to ~120 g/L (?)	high density, low-pressure	regeneration efficiency, two-way, cost

There is no perfect solution

Relationships between H_2 delivery and onboard storage options

		Storage Options					
		700 Bar	Cold-compressed	Cryo-compressed	Cryo-sorbent	Metal Hydride	Chemical Hydrogen
Delivery Options	Liquid H_2	✓	✓	✓	✓	✓	
	Low Pressure (< 200 bar)	✓	✓		✓	✓	
	High Pressure (> 200 bar)	✓	✓		✓	✓	
	Pipeline	✓	✓		✓	✓	
	Chemical Processing						✓
Forecourt Implications		Pre-cooling needed (down to -40 °C)	Refrigeration required (down to 150 K)	Supercritical H_2 needed (<< 150 K)	Liq H_2 or liq N_2 needed (down to 80 K) w/ recirculation	Heat rejection at forecourt maybe needed	Must recycle spent fuel offboard

Decisions on H_2 delivery method and onboard storage technology can create limitations on the available choice for the other

Thank you

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